Implementation of a Sealed Double-Ring Infiltrometer to Evaluate the Long-Term Hydraulic Performance of the Barrier Soil Layer Component of a Composite Landfill Cover System - Norridgewock, Maine

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May 2005

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1.0 EXECUTIVE SUMMARY

This report presents the results of a field and laboratory testing program undertaken to assess the hydraulic condition of the barrier soil layer component of a composite cover system on the former Municipal Solid Waste (MSW) Landfill at the Waste Management Disposal Services of Maine, Inc. (WMDSM) facility in Norridgewock, Maine. The project was completed during the summer of 2003 by the Division of Technical Services, Solid Waste Engineering Unit, as a follow-up to earlier studies completed over the previous ten years[1,2]. Access to the facility and logistical support were provided by WMDSM and H.E. Sargent, Inc. (HES) of Stillwater, Maine. Funding was provided by the Department's Division of Solid Waste Management.

The composite hydraulic barrier in the cover system evaluated consisted of a 40 mil co-extruded (composite density) geomembrane overlying approximately twelve inches of recompacted marine silty clay. The earlier studies all focused on compacted soil layers used as the sole barrier layer in landfill cover systems. We have previously hypothesized[2], based on numerous field observations, that the presence of an overlying geomembrane will allow a barrier soil layer to maintain its as-placed moisture condition, the loss of which we believe to be the primary contributor to hydraulic degradation. As of this writing, as part of their Phase 8 expansion, WMDSM is in the process of removing the MSW Landfill cover system and relocating the waste mass. The decommissioning of the cover system allowed us the opportunity to test our hypothesis and further our understanding of the mechanisms driving barrier soil layer hydraulic degradation.

The program consisted of the installation and monitoring of two Sealed Double-Ring Infiltrometer (SDRI) units, observation of the condition of the cover system, and the retrieval of thin-walled (Shelby) tube samples for laboratory testing. The SDRI, consisting of an open outer ring and sealed inner ring[3], allows for the direct measurement of the vertical infiltration rate into a soil mass over a large surface area (sixteen square feet with our apparatus). Vertical hydraulic conductivity can then be calculated from the infiltration rate using the measured hydraulic gradient. The tube samples were tested in the laboratory for water content and hydraulic conductivity using a flexible wall permeameter by Summit Geo-Engineering Services (Summit) of Augusta, Maine. The 2003 data was compared with the results of testing completed during construction of the final cover system in 1993. A third SDRI set-up was abandoned during installation when leakage was observed through a trench sidewall.

The results of this evaluation are somewhat mixed. The water content testing on soil samples removed prior to the initiation of SDRI testing at both test locations did, in fact, reveal that the moisture content of the barrier soil layer had not changed since its installation ten years earlier. Further, the exposed barrier soil layer appeared moist and cohesive with little evidence of desiccation cracking or other defects. These findings were as expected and in contrast with each of the other silty clay barriers previously investigated[4,5,6]. They appear to confirm that the placement of a geomembrane above and in direct contact with silty clay barrier soil layer prevents long-term moisture loss and the subsequent hydraulic degradation that is likely caused by it.

The calculated hydraulic conductivity at one of the SDRI test sites, WMDSM03, was $4.2x10^{-7}$ cm/sec which is somewhat greater than the geometric mean of the construction phase testing reported in 1993 ($8.5x10^{-8}$ cm/sec), however it falls well within the range of reported values and is nearly five times less than the arithmetic mean of the construction phase testing ($1.6x10^{-6}$ cm/sec). The laboratory samples removed from the WMDSM03 location indicated hydraulic conductivity values nearly identical to the geometric mean of the 1993 data. Also, construction acceptance of the barrier soil layer was based on a test pad program where all of the hydraulic conductivity data is from a particular test pad location and thus may not be fully indicative of localized conditions across the entire landfill cover. These factors lead us to believe that there may not have been any significant hydraulic degradation at WMDSM03 despite the calculated hydraulic conductivity being near the high end of the range of 1993 measured values. It is worth noting that the calculated hydraulic conductivity remains well below the specified maximum for the closure project of $1x10^{-6}$ cm/sec.

The calculated hydraulic conductivity at the other test site, WMDSM02, was an order of magnitude greater than WMDSM03 at $4.9x10^{-6}$ cm/sec. Based on direct observation of the condition of the barrier soil layer at WMDSM02, and previous experience at other sites, the measured infiltration rate did not seem realistic and led us to question whether leakage was occurring from the inner ring. A dye test conducted during removal of the equipment appeared to confirm seepage along the sidewall of the setup. For this and other reasons discussed in the report we have discounted the validity of the SDRI derived hydraulic conductivity data at WMDSM02. Other data (laboratory hydraulic conductivity and water content) and observations from the WMDSM02 location are believed to be reliable and valuable and will be treated as such within this report.

2.0 SITE DESCRIPTION

The WMDSM facility is an operating commercial solid waste landfill located off State Route 2 in Norridgewock, Maine (see Figure 1). The unlined MSW landfill at the facility began accepting municipal solid waste in 1976. In 1989, prior to acquisition of the site by WMDSM, a major landslide occurred and the landfill was subsequently stabilized and closed. At the time of our evaluation it occupied a footprint of approximately twenty-five acres. The final cover system consisted of, from top to bottom, a six inch layer of loamy topsoil, eighteen inches of sand, single- and double-sided drainage geocomposite, a 40 mil coextruded geomembrane, a twelve inch marine silty clay barrier soil layer, a geotextile, a six inch sand gas transmission layer, and six inches of intermediate cover. The top area of the landfill was graded at approximately five percent with sideslopes up to twenty percent. Elevations, as referenced to the National Geodetic Vertical Datum, ranged from 270 to 317 feet MSL at the time of closure. At the time of our investigation, a heavy, thick grass growth was present.

3.0 LABORATORY TESTING

3.1 Laboratory Testing for Landfill Closure (1993)

Laboratory testing of the barrier soil layer material for the landfill closure construction project in 1993[7] consisted of borrow source characterization and extensive testing of a pre-construction test pad. The material was obtained from an on-site borrow source and was characterized as a silty clay with a Plasticity Index ranging from 11 to 16. Borrow source testing for the entire project included 43 moisture-density compaction tests, 10 remolded hydraulic conductivity tests, 19 gradation analyses, 86 water content determinations, and 43 Atterberg limit tests.

The 10,000 square foot test pad was constructed on the north side of the MSW landfill (see Figure 2) to establish the construction procedures, equipment, and acceptance criteria that were used during full scale construction to achieve the specified barrier soil layer properties. Laboratory testing, conducted by Morrison Geotechnical Engineering of Waterville, Maine, occurred in two phases, pre-test pad and post-test pad. The pre-test pad testing was used to develop moisture-density relationships to guide test pad construction. The program included two moisture-density compaction tests, two gradation analyses, thirty hydraulic conductivity tests, two Atterberg limit tests, four specific gravity tests, and two water content determinations.

Post-test pad testing was used to document that the construction procedures, equipment, and moisture-density relationships utilized during test pad construction achieved the specification requirements, and thus could be successfully implemented during full-scale construction. The program included 16 water content determinations and 16 flexible wall hydraulic conductivity tests. The measured hydraulic conductivity values ranged from 1.2×10^{-8} to 1.8×10^{-5} cm/sec with a geometric mean of 8.5×10^{-8} cm/sec. The geometric mean, in lieu of the arithmetic mean, provides a more appropriate comparison because the 1993 data has a somewhat skewed range (see Table I). The water content ranged from 12.6 to 26.8 percent with an average of 19.9 percent. A complete summary of the data is included in Table I. Comprehensive Construction Quality Control (CQC) and Construction Quality Assurance (CQA) programs were implemented to assure that the test pad procedures were replicated during full-scale construction.

3.2 Barrier Soil Layer Sampling for this Evaluation (2003)

Two three-inch Shelby tube samples were retrieved prior to the installation of WMDSM02 and WMDSM03 by Technical Services personnel with assistance from HES. The samples were taken in the vicinity of the SDRI test locations and delivered to Summit the same day of recovery. The test holes were backfilled with soil.

Upon completion of the SDRI testing, four three-inch Shelby tube samples were retrieved from within the test area by Technical Services personnel with assistance from HES. The test holes were backfilled with soil and the samples were delivered to Summit.

3.3 Laboratory Testing for this Evaluation (2003)

Laboratory testing included two series of water content versus depth profiles and two hydraulic conductivity determinations for each SDRI test site.

Water content versus depth profiles at two inch intervals were evaluated before and after each of the SDRI tests (samples WM02A, WM06, WM03A, and WM05) to determine the depth of the wetting front. The depth of the wetting front is needed to determine the hydraulic gradient and, subsequently, calculate the hydraulic conductivity. Prior to the testing, the water content at WMDSM02 ranged from 18.7 to 20.1 percent with an average of 19.5 percent and the water content at WMDSM03 ranged from 20.6 to 23.4 percent with an average of 21.6 percent. The before and after profiles are presented graphically on Figures 3 and 4 and summarized in Table II.

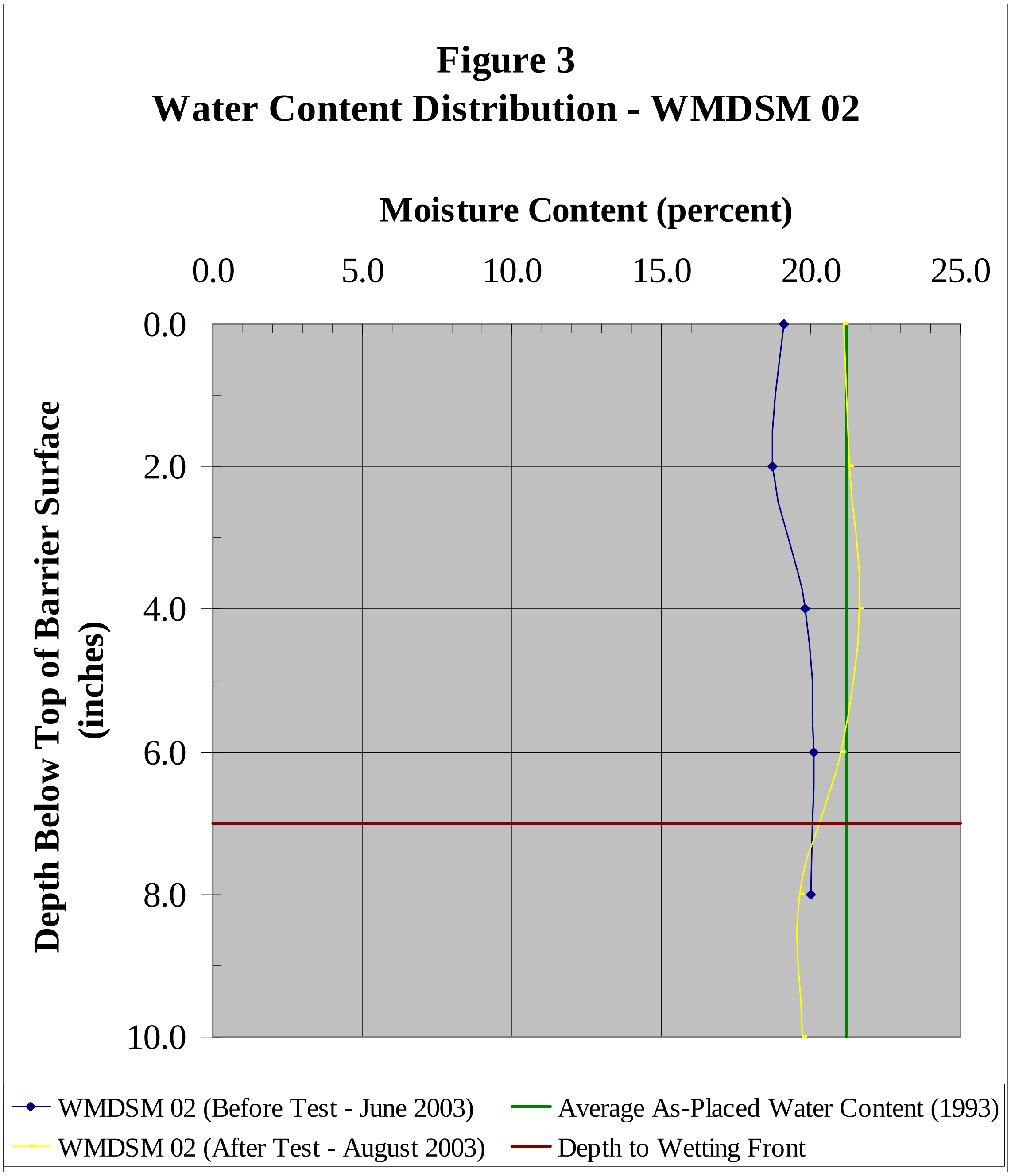


Figure 3
Water Content Distribution - WMDSM 02
Moisture Content (percent)
0.0
5.0
10.0
15.0
20.0
25.0
0.0
2.0
4.0
6.0
8.0
10.0
Depth Below Top of Barrier Surface (inches)
WMDSM 02 (Before Test - June 2003)
WMDSM 02 (After Test - August 2003)
Average As-Placed Water Content (1993)
Depth to Wetting Front

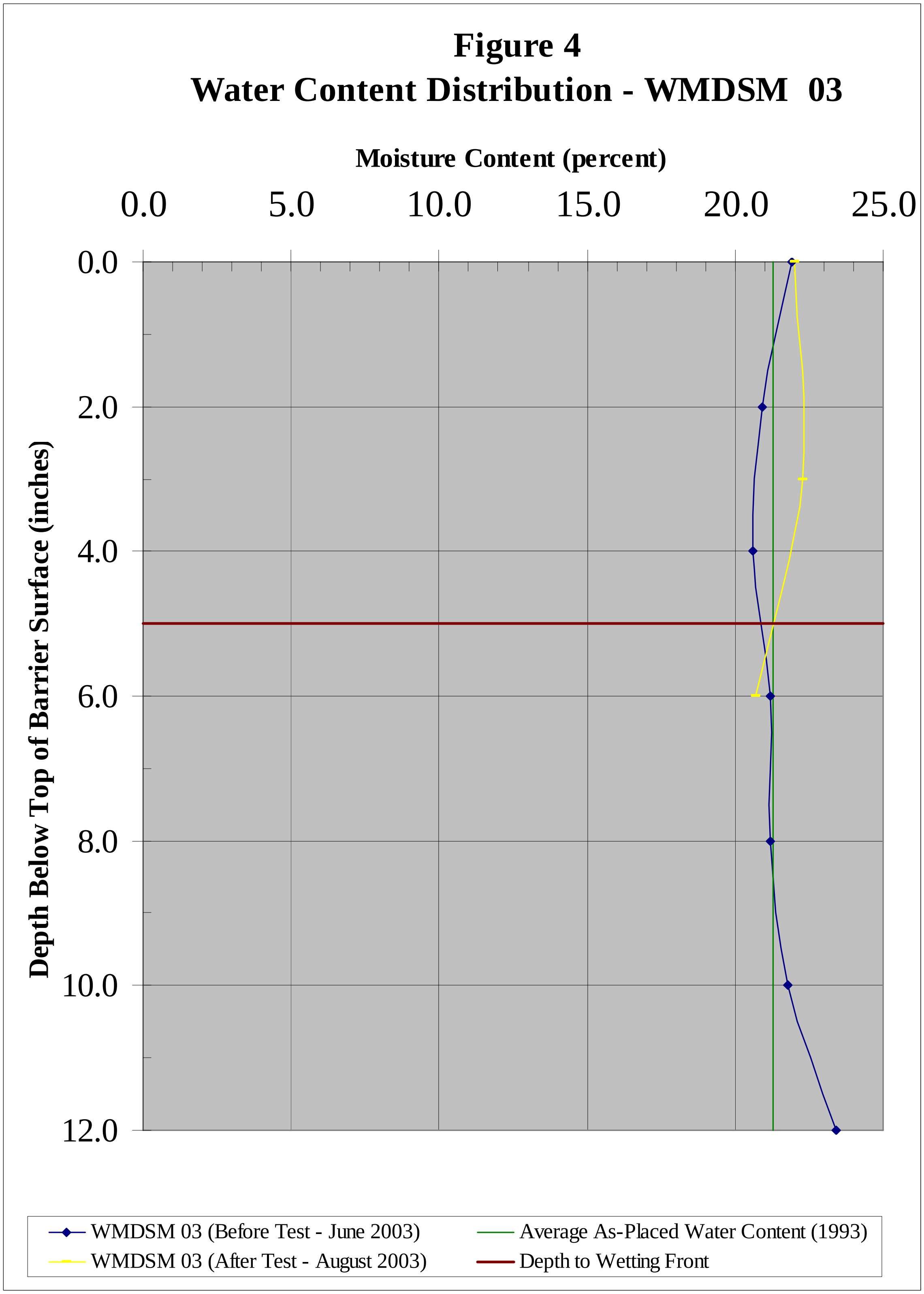


Figure 4
Water Content Distribution - WMDSM 03
Moisture Content (percent)
0.0
5.0
10.0
15.0
20.0
25.0
Depth Below Top of Barrier Surface (inches)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
WMDSM 03 (Before Test - June 2003)
WMDSM 03 (After Test - August 2003)
Average As-Placed Water Content (1993)
Depth to Wetting Front

TABLE I

SUMMARY OF 1993 LABORATORY HYDRAULIC CONDUCTIVITY TESTING
WMDSM - CROSSROADS LANDFILL
NORRIDGEWOCK, MAINE

Sample #	Depth Below Barrier Soil Surface (inches)	Natural Water Content (%)	Hydraulic Conductivity (cm/sec)
93-138	5.0-8.0	22.7	2.0E-08
93-138	9.0-12.0	22.9	2.7E-08
93-139	3.0-6.0	24.0	2.9E-08
93-140	11.0-14.0	19.7	1.5E-08
93-148	9.0-12.0	20.3	1.3E-08
93-149	10.0-13.0	26.8	3.1E-08
93-149	5.5-8.5	18.9	1.0E-07
93-151	2.0-5.0	17.2	4.3E-08
93-151	5.0-8.0	20.2	1.6E-08
93-177	3.0-6.0	16.3	3.6E-06
93-178	6.5-9.5	14.6	2.7E-06
93-179	9.5-12.5	12.6	1.2E-07
93-181	2.0-5.0	19.9	2.3E-08
93-182	3.0-6.0	16.7	2.4E-08
93-184	6.0-9.0	18.9	9.9E-08
93-185	3.0-6.0	26.2	1.8E-05

Notes:

1. Laboratory testing was conducted by Morrison Geotechnical Engineering of Waterville, Maine. Soil samples were tested in accordance with ASTM D 5084, Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter, Method A (Constant Head).

2. Testing locations were selected by GZA GeoEnvironmental, Inc. of Portland, Maine.

Tube samples WM07 and WM04 were taken to the laboratory for hydraulic conductivity testing. Test specimens were cut from the top and bottom portions of the sample. The water content was also measured. The laboratory measured hydraulic conductivity values from WMDSM02 were 3.4×10^{-8} and 1.9×10^{-8} cm/sec. The laboratory measured hydraulic conductivity values from WMDSM03 were 7.0×10^{-8} and 8.7×10^{-8} cm/sec. The data is summarized in Table III and the laboratory reports are included in Appendix A.

TABLE II

SUMMARY OF 2003 LABORATORY WATER CONTENT TESTING
WMDSM - CROSSROADS LANDFILL
NORRIDGEWOCK, MAINE

Location	Sample #	Water Content Range (%)	Water Content Average (%)
WMDSM02 (before)	WM02A	18.7-20.1	19.5
WMDSM02 (after)	WM06	19.6-21.6	20.7
WMDSM03 (before)	WM03A	20.6-23.4	21.6
WMDSM03 (after)	WM05	20.7-22.3	21.7

Notes:

1. Samples WM02A and WM03A were retrieved on June 2 and June 4, 2003 respectively. Samples WM05 and WM06 were retrieved on August 15, 2003. All samples were retrieved by Technical Services personnel with assistance from H.E. Sargent, Inc. of Stillwater, Maine.

2. Laboratory testing was performed by Summit Geo-Engineering Services of Augusta, Maine in general accordance with ASTM D 2216, Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock.

3. Water Content Range reflects the variation throughout the entire depth of the soil sample profile.

4.0 IN-SITU TESTING

4.1 In-Situ Testing for Landfill Closure (1993)

In-situ testing performed on the barrier soil layer during construction consisted of 695 field moisture-density tests with a nuclear densometer (ASTM D 3017 and ASTM D 2922) and 27 field sand cone density tests (ASTM D 1556), done for confirmatory purposes. Field testing was performed by GeoSyntec Consultants of Atlanta, Georgia.

We selected moisture test results from measurements taken in the vicinity of each of the SDRI test sites for comparison with our findings during this evaluation. The water content from the selected tests in the vicinity (within about a 30 foot radius) of WMDSM02 ranged from 18.3 to 23.2 percent with an average of 21.2 percent and the water content from the selected tests in the vicinity (within about a 30 foot radius) of WMDSM03 ranged from 19.6 to 22.9 percent with an average of 21.3 percent. The data is summarized in Table IV.

TABLE III

SUMMARY OF 2003 LABORATORY HYDRAULIC CONDUCTIVITY TESTING
WMDSM - CROSSROADS LANDFILL
NORRIDGEWOCK, MAINE

Location	Sample #	Depth Below Barrier Surface (feet)	Natural Water Content (%)	Hydraulic Conductivity (cm/sec)
WMDSM02	WM07	0.17	24.2	3.4E-08
WMDSM02	WM07	0.58	19.8	1.9E-08
WMDSM03	WM04	0.12	22.8	7.0E-08
WMDSM03	WM04	0.83	21.6	8.7E-08

Notes:

1. Samples WM04 and WM07 were retrieved on August 15, 2003 in the vicinity of WMSDM02 and WMDSM03 respectively by Technical Services personnel with assistance from H.E. Sargent, Inc. of Stillwater, Maine.

2. Samples were retrieved using undisturbed sampling techniques and were tested in the laboratory by Summit Geo-Engineering Services of Augusta, Maine in general accordance with ASTM 5084, Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter.

TABLE IV

SUMMARY OF 1993 FIELD WATER CONTENT TESTING
WMDSM - CROSSROADS LANDFILL
NORRIDGEWOCK, MAINE

Location	Water Content Range (%)	Water Content Average (%)
Vicinity of WMDSM02	18.3-23.2	21.2
Vicinity of WMDSM03	19.6-22.9	21.3

Notes:

1. Testing was performed by GeoSyntec Consultants of Atlanta, Georgia in general accordance with ASTM D 3017, Standard Test Method for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth).

4.2 Barrier Soil Layer Condition at the SDRI Test Sites (2003)

The condition of the barrier soil layer was observed at each of the SDRI test sites following removal of the geomembrane. In all cases the surface was noted to be moist with a slightly blocky structure and only minimal abrasion from the textured geomembrane was evident. Minor surficial cracking was observed at one of the test sites. No stones were encountered. Upon removal of the Shelby tubes, and during excavation of the trenches for the inner rings, the barrier soil layers were observed throughout their entire thicknesses and were noted to be homogeneous and moist. Photographs of the barrier soil layer condition are included in Appendix B.

4.3 In-Situ Testing for this Evaluation (2003)

In-situ testing for this evaluation consisted of two SDRI tests, WMDSM02 and WMDSM03. A third SDRI test, designated WMDSM01 and located adjacent to the WMDSM03 set-up, was abandoned during installation due to observed piping of water through a trench sidewall. The testing was performed in general accordance with ASTM D 5093, Standard Test Method for Field Measurement of Infiltration Rate Using a Sealed Double-Ring Infiltrometer with a Sealed Inner Ring. Approximate locations of the SDRI test sites are illustrated on Figure 5 and a copy of the ASTM test method is included as Appendix C.

The SDRIs were installed during the period from June 2 through June 5, 2003 by Technical Services personnel with assistance from HES. Both tests were run for 67 days from June 6 through August 12, 2003. A total of 14 measurements were taken from WMSDM02 and 19 measurements from WMDSM03. The resulting infiltration rates were found to be 1.3×10^{-5} cm/sec at WMDSM02 and 1.2×10^{-6} cm/sec at WMDSM03. After interpreting the water content profiles, hydraulic conductivity values of 4.9×10^{-6} and 4.2×10^{-7} cm/sec respectively were calculated. The data is presented graphically on Figures 6 and 7 and summarized in Table V.

Figure 6
SDRI Infiltration Rate Versus Time - WMDSM 02

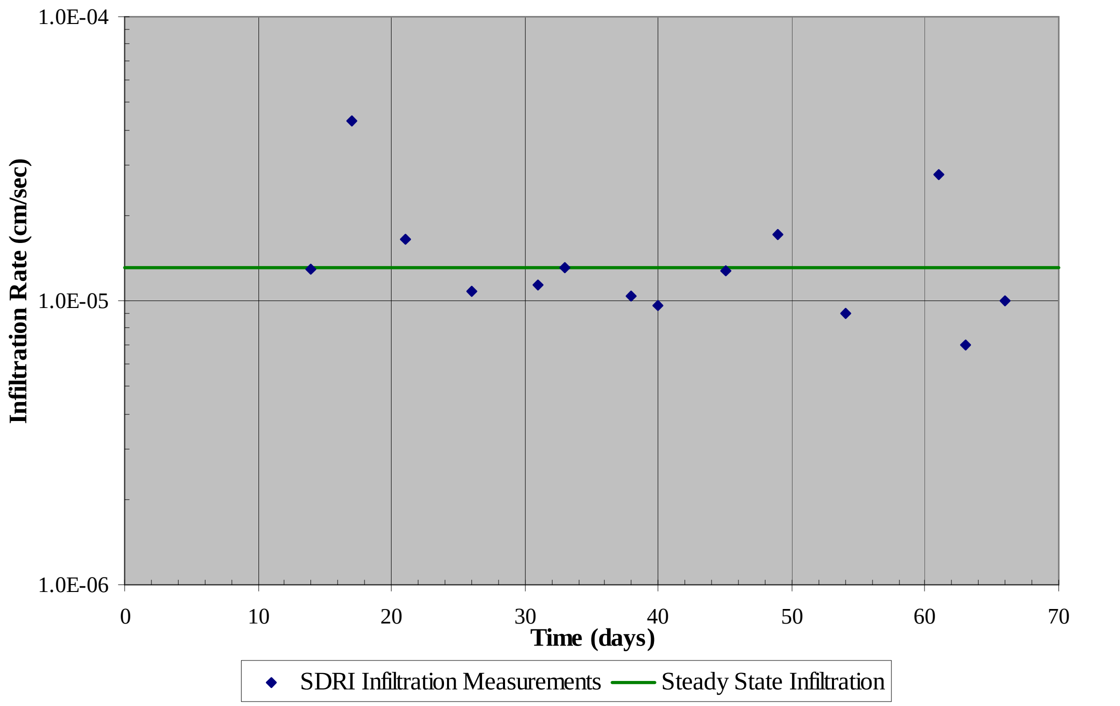


Figure 7
SDRI Infiltration Rate Versus Time - WMDSM 03

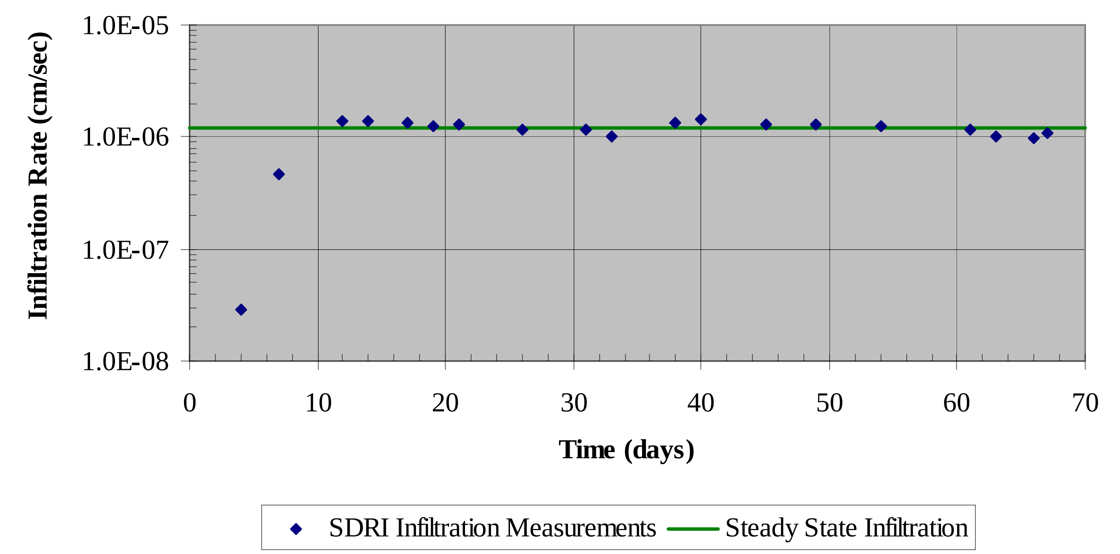


TABLE V

SUMMARY OF 2003 FIELD SDRI TESTING
WMDSM - CROSSROADS LANDFILL
NORRIDGEWOCK, MAINE

Location	Infiltration Rate (cm/sec)	Depth to Wetting Front (ft)	Hydraulic Conductivity (cm/sec)
WMDSM02	1.3E-05	0.58	4.9E-06
WMDSM03	1.2E-06	0.50	4.2E-07

Notes:

1. Field testing was conducted by Technical Services personnel in general accordance with ASTM D 5093, Standard Test Method for Field Measurement of Infiltration Rate Using a Double-Ring Infiltrometer with a Sealed-Inner Ring.

2. Field testing was performed from June 6 through August 12, 2003.

5.0 SDRI TEST SUMMARY

5.1 Significance and Use

The SDRI test, as outlined by ASTM D 5093, provides a means to determine the low infiltration rates associated with fine grained, clayey soils. It is designed to measure the actual volume of water flowing into the soil mass over a period of time rather than a drop in elevation head, as is the case with most other infiltration test procedures. The configuration of the apparatus (see Figure 8a) ensures that flow into the area of question is essentially one-dimensional (vertical). Its size (Figure 8b) allows the measurement to be made over a relatively large area of soil. Tests on large volumes of soil are likely to be more representative of the performance of the barrier soil layer as a whole than tests on small volumes, such as tube samples removed for laboratory testing, due to the ability to encompass large scale preferential flow paths (Figure 8c).

Figure 8a: Sealed Double-Ring Infiltrometer (cross-sectional view)

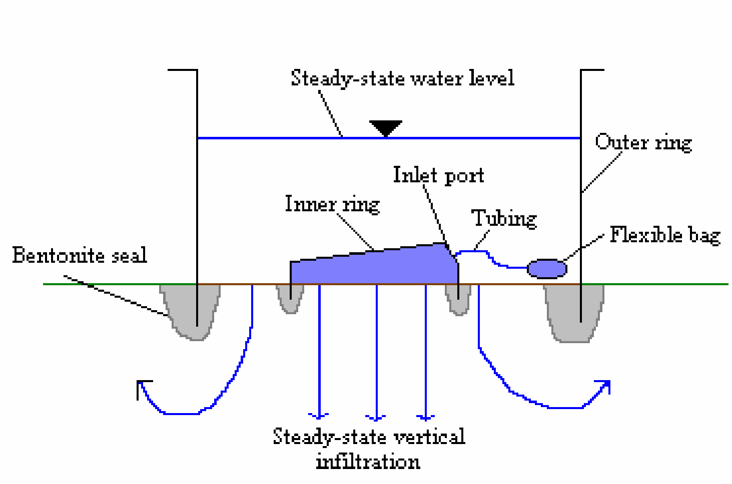


Figure 8b: Sealed Double-Ring Infiltrometer (plan view)

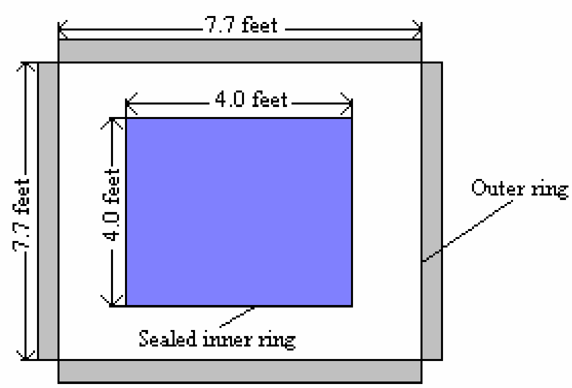
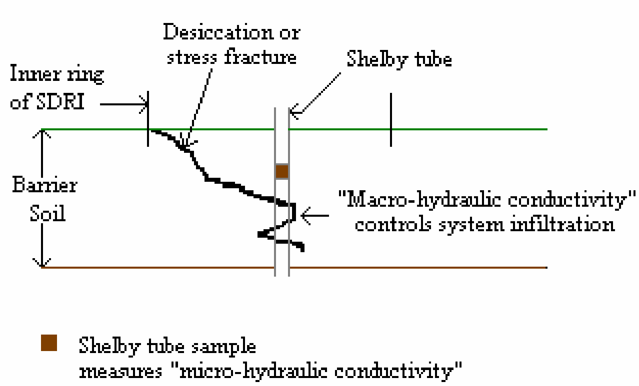


Figure 8c: Preferential Flow Path



5.2 Apparatus

The SDRI consists of two rings, a sealed inner ring and an open outer ring. The two SDRIs used for this evaluation were fabricated by W.A. Messer, Inc. of Westbrook, Maine. The outer rings are made up of four 7.7 foot long by three foot high eighth-inch thick aluminum panels bolted together. In plan dimension they form a 7.7 foot by 7.7 foot square when assembled. The sealed inner rings, also fabricated from eighth-inch thick aluminum, are individual units that form a six to fifteen inch high, four foot by four foot enclosed square with a sloping top that provides a high point for the accumulation of any air trapped in the system. Two ports for flexible tube connections are provided near the high point. Figure 9 provides details of the SDRI apparatus and photographs are included in Appendix B.

5.3 SDRI Installation

Following site selection, which should be an area with a surface slope less than about 3 percent, the overburden above the barrier layer is removed over an area of approximately 12 feet by 12 feet using caution not to damage the barrier. A 4 to 5 inch deep trench, approximately 2 inches wide, is cut into the barrier soil layer following the plan dimensions of the inner ring such that its base is at a constant elevation. The trench is then filled with a bentonite grout mix, the inner ring is placed into it, and an amount of water sufficient to check for leaks is siphoned into the ring. Once a leak free system is established and the inner ring is set, the entire test area is covered with plastic sheeting to prevent the loss of moisture from the barrier soil.

The outer ring panels are then bolted together using rubber gaskets and caulk to seal the corners. A 12 to 18 inch deep trench, depending on the thickness of the barrier soil layer, approximately 4 inches wide is cut following the plan dimensions of the outer ring centered around the inner ring. The outer ring is then placed into the trench and the inside and outside sealed with bentonite grout.

With both rings in place, the outer ring is filled with water while leaving the lower port of the inner ring open to allow it to fill. A tube and valve are attached to the upper port of the inner ring to allow the displaced air to bleed out. The outer ring is filled to an elevation about 6 inches above the top of the inner ring. At the same time, an earthen berm is placed against the outside wall of the outer ring to counteract the hydrostatic force against the inside of the wall. Once the rings are full an insulated cover is bolted over the outer ring to limit the effects of thermal expansion and contraction on the system. The entire apparatus is then covered with a tarp to shed precipitation and shade the system from the sun.

5.4 WMDSM01

The location for WMDSM01 was selected by Technical Services personnel during a site reconnaissance on April 29, 2003. It was located on a fairly level plateau on the landfill surface to the northeast of the area of peak elevation. A good stand of vegetation was present.

Removal of the overburden by backhoe began early in the afternoon on June 2. As expected, six inches of topsoil and eighteen inches of sand were encountered and removed from above the drainage geocomposite. The single-sided drainage geocomposite and geomembrane were cut out of the area and both were observed to be intact and in good condition. A geomembrane seam was encountered including a destructive test patch marked “# 263 MX3 8/17 AM”. The barrier soil layer condition was as described in Section 4.2. The maximum slope across the surface was measured to be approximately three percent. The inner trench was hand excavated and the area secured by the end of the day.

The inner ring was installed and filling began on the afternoon of June 3, concurrent with the excavation of the outer ring using a gasoline powered trenching machine. During excavation of the outer trench, piping was noted through the trench wall from water being siphoned into the inner ring. The cause of the piping was not readily apparent but was likely the result of installation damage. The installation was abandoned and a new location, WMSDM03, was selected about 30 feet to the northeast of WMDSM01. The area was backfilled and stabilized on June 4. Note that the cover system was not restored to its original condition because it was to be dismantled within a few months.

5.5 WMDSM02

The location for WMDSM02 was also selected by Technical Services personnel during the site reconnaissance on April 29, 2003. It was located in a similar setting as WMDSM01 but to the southeast of the area of peak elevation.

The overlying topsoil, sand, drainage geocomposite, and geomembrane were removed from the area on the afternoon of June 2. The condition of all materials was similar to what was encountered at WMDSM01, however the drainage geocomposite was found to be double-sided. A Shelby tube, WM02A, pushed into the soil barrier layer encountered the underlying geotextile at 10.75 inches beneath the surface. The maximum slope across the surface was measured to be approximately four percent. The inner trench was hand excavated and the site secured early in the evening on June 2.

The inner ring was placed and sealed and water was siphoned into it on the morning of June 3. No leakage was observed and the installation and filling of the outer ring of WMDSM02 was completed by the end of the day. The static water level was subsequently measured and the site secured.

5.6 WMDSM03

WMDSM03 was installed on June 4, 2003 following the same procedures used to install WMDSM02. The material conditions were found to be similar to those observed at WMDSM01 and WMDSM02. The grade of the barrier soil layer was found to be generally flat. No problems were encountered and the installation and filling was completed by the end of the day.

Installation photographs are included in Appendix B.

6.0 SDRI MEASUREMENTS

6.1 Procedures

At the completion of its installation the SDRI is left with an open tube, immersed in the water, connected to the lower port of the inner ring and a tube with a closed air valve connected to the upper port. A thermometer is left immersed in the water of the outer ring and a measuring tape is placed on the inside wall of the outer ring to monitor the water level. An additional thermometer is secured to the cover of the SDRI in a shaded location to monitor the ambient air temperature. A flexible bag, connected to a tube with a ball (on/off) valve, a clock, and a scale are required to take the measurements. The following procedures are undertaken to initiate a reading:

1. Record the water level in the outer ring.

2. Open the air valve to bleed out any air accumulated in the inner ring, then close the valve.

3. Record the water temperature in the outer ring.

4. Record the ambient air temperature.

5. Fill the flexible bag with water and weigh it.

6. Connect the bag to the lower port of the inner ring and open the valve.

7. Record the time and date.

The following procedures are undertaken to complete a reading:

1. Record the water level in the outer ring. Add water if the level has dropped more than about one inch from its level at the time the SDRI was installed.

2. Record the water temperature in the outer ring.

3. Record the ambient air temperature.

4. Close the valve to the flexible bag and record the time and date.

5. Weigh the flexible bag.

Readings continue until the infiltration rate reaches a steady state. Data taken for the individual readings at WMDSM02 and WMDSM03 are included in Appendix D. The infiltration rates are graphically presented on Figures 6 and 7. It is noteworthy that, as can be seen on Figure 6, there is significant scatter in the data for WMDSM 02 indicating instabilities in the system.

6.2 WMDSM02

The first reading at WMDSM02 was set up at 11:10 am on June 9, 2003 with an initial bag/valve/water weight of 16.30 pounds. The bag was checked on the morning of June 10 and found to be empty. On June 11 the weight of the bag and valve without any water was measured to be 1.36 pounds, therefore 14.94 pounds, or 2.00 gallons, of water escaped the bag in less that 24 hours. The high rate of infiltration was not expected and the bag was refilled and checked for leakage along with the tubing and valve. No leakage was found and another reading was initiated at 1:39 pm that day with a recorded weight of 17.58 pounds.

WMDSM02 was next checked on the morning of June 13 and the bag was again found to be empty. The equipment was again checked for leaks and none were found. The decision was made to let the set-up stabilize for a few days.

The next attempt at a reading took place on June 18. A new bag, valve, and tube, equipment known to be functioning properly from the WMDSM03 set-up, was used. The reading was started at 1:32 pm with a combined weight of 16.72 pounds. At 1:09 pm on June 19 the bag was again found to be empty.

On June 20 an attempt was made to take a reading over a shorter time interval. The reading was started at 11:40 am with a combined weight of 18.64 pounds. At 1:12 pm the bag was disconnected and found to weigh 16.68 pounds, a loss of 1.96 pounds, or 0.26 gallons, in 112 minutes. The decision was made to continue taking readings over shorter time intervals.

A total of 14 successful readings were recorded between June 20 and August 12. A steady state infiltration rate of 1.3×10^{-5} cm/sec was estimated. Due to scatter in the data a steady state infiltration rate could only be approximated.

6.3 WMDSM03

The first reading at WMSDM03 was set up at 11:44 am on June 9 with an initial combined weight of 15.38 pounds. The bag was disconnected at 3:15 pm on June 10 and a combined weight of 15.30 pounds was recorded. The loss of only 0.08 pounds in about 27.5 hours was less than expected and is likely attributable to the swelling of bentonite inside the inner ring. The second reading, recorded on June 13, showed an increase in the rate of water loss.

The third reading was recorded on June 18 and showed a loss of 16.72 pounds over a period of just over five days, converting to an infiltration rate of about 1.2×10^{-6} cm/sec. From there the infiltration rate remained steady for 17 readings over the next 55 days. A steady state infiltration rate is clearly discernable on Figure 7. The last reading was taken on August 12.

6.4 Calculation of Hydraulic Conductivity

Once the steady-state infiltration rate (I) has been determined the hydraulic conductivity (K) can be calculated using the following equations:

$$K = I / i \quad \text{and} \tag{eq. 1}$$

$$i = (H + L_f + \Psi) / L_f \tag{eq. 2}$$

where: i = the hydraulic gradient,
H = the depth of ponded water in the outer ring,
L_f = the depth of the wetting front, and
Ψ = the wetting front suction head.

As discussed earlier, the depth of the wetting front is determined by profiling the water content of the barrier soil layer before and after the SDRI test. The laboratory measured water content profiles are depicted graphically on Figures 3 and 4. The depths to the wetting fronts were determined to be seven inches at WMDSM02 and five inches at WMDSM03. The wetting front suction head is assumed to be zero[8].

7.0 SDRI REMOVAL AND SITE RESTORTAION

7.1 Removal of Test Apparatus

The SDRI apparatus was dismantled and removed from the site on August 12, 13, and 15, 2003 by Technical Services personnel with assistance from HES. Water was pumped from the outer rings and the inner rings were subsequently allowed to drain. The panels were removed from the barrier soil layer trenches and disassembled.

Prior to allowing the water to drain from the inner ring at WMDSM02 dye was injected into it, using the flexible bag, to check for leakage along the ring sidewall. A distinct point discharge from the ring was quickly evident over a length of about an inch on one side of the ring. Attempts to carefully excavate the area of the discharge were difficult due to saturated conditions and movement from lifting the ring out, however, it appeared that there had been a fissure, possibly due to installation damage, from the edge an inch or two back into the soil mass. Photographs of the dye discharge are included in Appendix B.

7.2 Site Restoration

Prior to restoring the cover, Shelby tube samples were retrieved by Technical Services personnel, with assistance from HES, for water content and hydraulic conductivity testing. The cover system was not restored to its original condition because it was to be dismantled within a few months. The geomembranes and drainage geocomposites were placed back onto the barrier soil layer surface but not seamed. The sand and topsoil were replaced by HES using a backhoe. The test areas were subsequently seeded and mulched.

8.0 SUMMARY AND DISCUSSION

8.1 WMDSM02

SDRI WMDSM02 was installed on June 2 and 3, 2003. The infiltration rate at WMDSM02 was higher than anticipated making it necessary to take the measurements over fairly short time intervals (no more than a few hours). The first successful reading was recorded on June 20 followed by 13 additional measurements over a 55 day period. Although there is some scatter, the data indicate that an approximate steady state infiltration rate was reached about 20 days following installation. The scatter may, at least in part, be due to the shorter time intervals of the measurements. The SDRI was dismantled and the site restored on August 12, 13, and 15.

The final calculated hydraulic conductivity for WMDSM02 was 4.9×10^{-6} cm/sec based on an estimated steady state infiltration rate of 1.3×10^{-5} cm/sec and an estimated gradient of 2.38. Two laboratory measurements conducted on a tube sample taken from within the area of the inner ring following its removal indicated hydraulic conductivities of 3.4×10^{-8} and 1.9×10^{-8} cm/sec respectively. The 1993 and 2003 hydraulic conductivity data are compared graphically with respect to depth on Figure 10. Figure 11 depicts the range of measurements over time. The water content of the barrier soil layer measured prior to the test (ten years following construction) averaged 19.5 percent.

When it was uncovered the barrier soil layer at WMDSM02 was moist, its surface was smooth, and no appreciable cracking or desiccation was observed (see photographs in Appendix B).

Based on our observation of its condition and the water content profile taken before the test, it is readily apparent that the barrier soil layer at WMDSM02 maintained its moisture properties over the ten year period following its installation. The average moisture content from the water content profile of 19.5 percent is essentially the same as the average of 19.9 percent reported at the time of construction (the measured moisture content in the vicinity of the SDRI set-up averaged 21.2 percent).

The estimated SDRI determined hydraulic conductivity was an order of magnitude greater than the geometric mean of the hydraulic conductivity measured at the time of construction. Based on the moisture maintenance described above, and the lack of cracking or desiccation leading to preferential flow paths, the SDRI estimated hydraulic conductivity at WMDSM02 does not seem reasonable. We believe that the high hydraulic conductivity measured with the SDRI was due to sidewall leakage from the inner ring and is not indicative of the actual hydraulic properties of the barrier soil layer at the time of our investigation. The following would appear to justify our conclusion:

- The laboratory samples extracted at WMDSM02 indicated hydraulic conductivity values near the low end of the 1993 data and two orders of magnitude lower than the estimated SDRI value.

- The wetting front advanced only about half way through the barrier soil layer during SDRI testing, about the same as it did at WMDSM03 over the same period of time. A comparison of the infiltration rates and wetting front progressions indicates that the inner ring of WMDSM02 was losing water to mechanisms other than just vertical infiltration.

- There was significant scatter in the measured infiltration rates during the testing, an indicator of system instability.

- A dye test conducted when the equipment was being dismantled appeared to confirm a leak.

8.2 WMDSM03

SDRI WMDSM03 was installed on June 4, 2003 as a replacement for WMDSM01 that was abandoned due to leakage from the inner ring sidewall. The first successful reading was recorded on June 10 followed by an additional 18 measurements over a 65 day period. The measurements were taken over time intervals ranging from one to five days. The data indicate that a steady state infiltration rate was reached approximately twelve days following installation. The SDRI was dismantled and the site restored on August 12, 13, and 15.

The final calculated hydraulic conductivity for WMDSM03 was 4.2×10^{-7} cm/sec based on a clearly defined steady state infiltration rate of 1.2×10^{-6} cm/sec and an estimated gradient of 2.85. Two laboratory measurements conducted on a tube sample taken from within the area of the inner ring following its removal indicated hydraulic conductivities of 7.0×10^{-8} and 8.7×10^{-8} cm/sec respectively. The 1993 and 2003 hydraulic conductivity data are compared graphically with respect to depth and time on Figure 12. Figure 13 depicts the range of measurements over time. The water content of the barrier soil layer measured prior to the test (ten years following construction) averaged 21.6 percent.

When it was uncovered the barrier soil layer at WMDSM03 was moist, its surface was smooth, and no appreciable cracking or desiccation was observed (see photographs in Appendix B).

Similar to the barrier soil layer at WMDSM02, it is readily apparent that the barrier soil layer at WMDSM03 maintained its moisture properties over the ten year period following its installation. The average moisture content from the water content profile of 21.6 percent is consistent with the average of 19.9 percent reported at the time of construction (the measured moisture content in the vicinity of the SDRI set-up averaged 21.3 percent).

While slightly higher than the geometric mean, the SDRI determined hydraulic conductivity from 2003 falls within the range of values measured from the tube samples taken during the development of a test pad prior to full-scale construction during 1993. For a number of reasons, we believe the SDRI derived value to be indicative of the condition of the barrier soil layer at the time it was placed. In general, a construction phase test pad provides a window of what to expect during full-scale construction. As construction progresses one can expect at least some degree of variation in borrow soil characteristics, weather conditions, and soil response to compaction. Further, the moisture content, lack of any significant desiccation, and observable homogeneity of the soil all point to the maintenance of as-placed properties. Finally, the laboratory hydraulic conductivities measured from the two tube samples extracted following SDRI testing compare favorably with the construction phase testing (see Figure 13).

9.0 CONCLUSIONS AND RECOMMENDATIONS

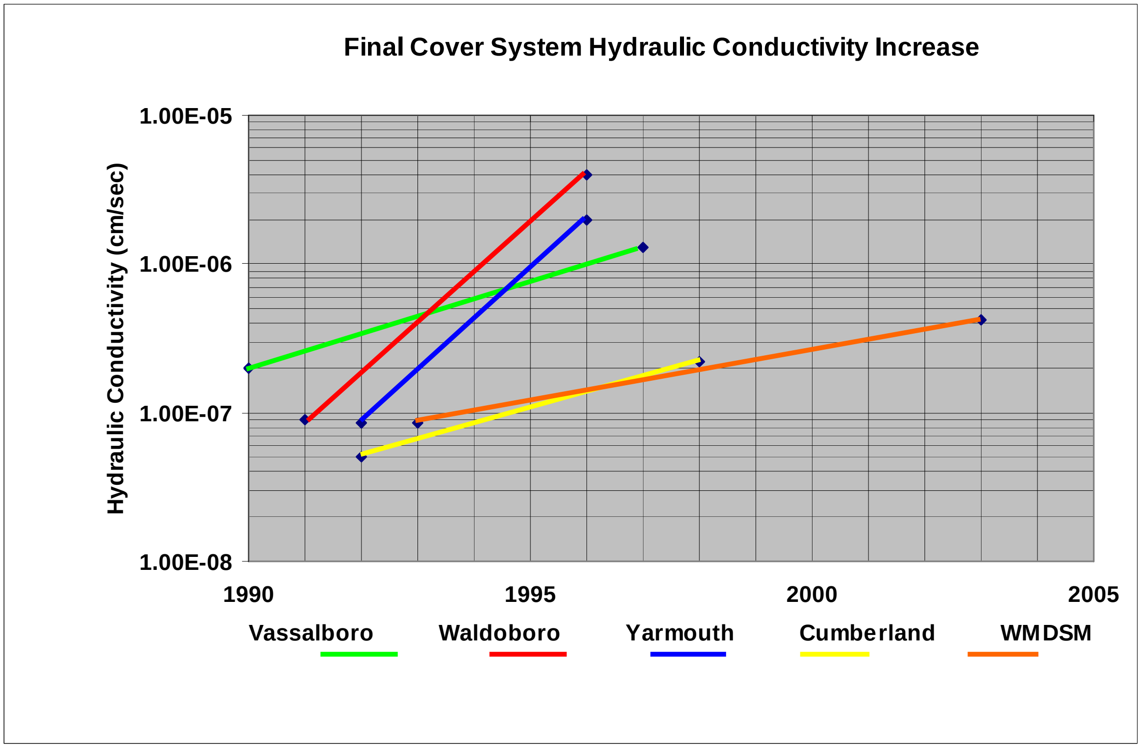
The conclusions and recommendations presented herein are based on our historical observations of the condition of barrier soil layers exposed after being covered with geomembranes for a period of time and the results of the WMDSM investigation. We are unaware of any study similar to what we conducted at WMDSM, therefore these conclusions and recommendations should be used with some degree of caution.

9.1 Conclusions

1. The installation of a geomembrane above and in direct contact with a barrier soil layer in a landfill cover system provides for the maintenance of as-placed soil moisture and hydraulic properties. Conversely, as found in previous studies[1,2], barrier soil layers installed without an overlying geomembrane will undergo significant drying, desiccation, and, subsequently, decreased hydraulic performance over time.

   Figure 14a graphically depicts the measured change in hydraulic conductivity over time for each of the five barrier soil layers studied using the SDRI since 1993. Visually, the WMDSM barrier soil layer (represented by the orange line), overlain by a geomembrane, has undergone the least amount of hydraulic degradation, if any appreciable degradation has in fact occurred. As discussed previously there is no as-built hydraulic conductivity data from the vicinity of the SDRI set-up due to the test pad approach used to guide construction of the barrier soil layer. The SDRI derived hydraulic conductivity falls within the range of values measured within the test pad in 1993 and may in fact reflect as-placed conditions at the test site. It should be noted that the SDRI data from WMDSM depicted on Figure 14a is limited to that collected at WMDSM03.

Figure 14a



The other four barrier soil layers were not overlain by a geomembrane. SDRI tests at Waldoboro and Yarmouth (red and blue lines respectively) revealed very similar trends of significant hydraulic degradation. Vassalboro (green line) also showed significant degradation, although not to the extent of Waldoboro and Yarmouth. The barrier soil layer at Vassalboro was constructed of a glacial till material which, by its nature, is not subject to the same degree of moisture loss and cohesive desiccation as the silty clay materials used at the other sites[1,2,9,10].

The findings from the Cumberland site (yellow line) would appear to contradict a conclusion that an overlying geomembrane is required to maintain the barrier soil layer moisture. In reviewing the data[6] from the 1998 SDRI test, however, it is noted that it took in excess of 60 days to achieve a steady state infiltration rate indicating that the hydraulic performance may have been controlled by the lower silty clay strata (the upper soils may have been degraded). Conversely, the 2003 WMDSM SDRI reached steady state in less than twelve days indicating a consistent condition throughout the profile. As discussed in a previous report[1], we believe that, with time, degradation will progress through the entire profile of the Cumberland barrier soil layer resulting in a hydraulic performance similar to what was measured at Waldoboro and Yarmouth.

To better illustrate the magnitude of the difference in hydraulic properties at the sites studied, the measured hydraulic conductivity data, plotted logarithmically on Figure 14a, was converted from cm/sec to ft/year and is plotted on a linear scale on Figure 14b. Again, the WMDSM SDRI data depicted on Figure 14b is limited to that collected at WMDSM03.

2. The primary factor controlling the hydraulic degradation of cohesive (silty clay) barrier soil layers is long-term moisture loss and subsequent desiccation.

   Figure 15 graphically depicts the correlation between moisture loss over time and a trend of increasing hydraulic conductivity for the silty clay barrier soil layers studied using the SDRI apparatus. As can be seen, the barrier soil layers at both Waldoboro (1993 and 1996) and Yarmouth (1994 and 1996) saw very similar trends of on-going moisture loss with corresponding increases in hydraulic conductivity. The Cumberland barrier soil layer, on the other hand, had relatively little overall moisture loss and saw a much smaller increase in hydraulic conductivity (see above). It is our belief that all three of these barrier soil layers will eventually reach a steady state moisture condition with a static hydraulic conductivity on the order of $1x10^{-5}$ cm/sec.

   In the case of WMDSM the moisture content of the barrier soil layer was essentially unchanged from when it was placed ten years previous. While a relatively small increase in hydraulic conductivity is reported, we believe, for reasons discussed previously, that it may actually be representative of the as-placed condition.

3. The test pad method, including implementation of comprehensive CQC and CQA programs, provides a sound approach for assuring that a barrier soil layer will be adequately constructed to meet its initial performance objectives.

   The WMDSM barrier soil layer was installed in 1993 in accordance with methods and moisture-density relationships determined during construction of a demonstration test pad where hydraulic conductivity was extensively evaluated. Comprehensive CQC and CQA programs were implemented to assure that the test pad procedures were replicated during full-scale construction. Even ten years after installation the measured moisture properties and hydraulic conductivity were well within the range documented during test pad construction.

4. Testing of barrier soil layer samples, extracted from thin walled Shelby tubes, using a laboratory flexible wall permeameter provides a reasonably accurate indication of hydraulic conductivity when large-scale cracking, or other large scale imperfections, are not present.

Figure 14b

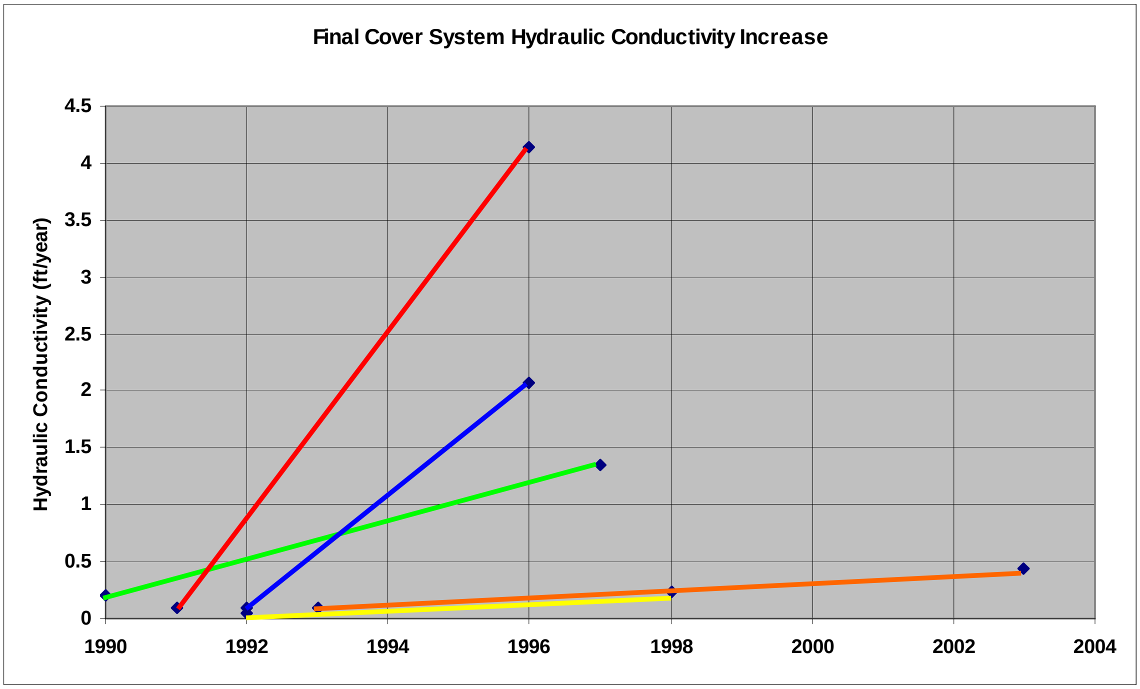
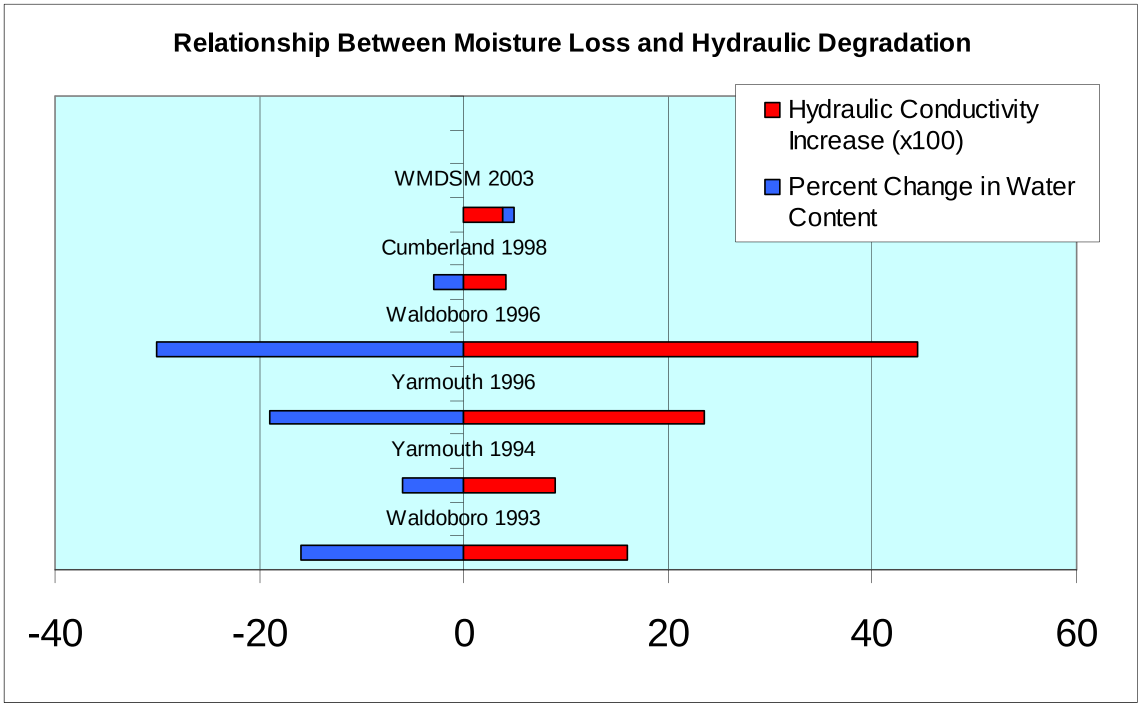


Figure 15



2003 hydraulic testing of Shelby tube samples extracted from the barrier soil layer within the WMDSM landfill cover system compared reasonably well with the SDRI test results. We would expect this in barrier soil layers where large-scale desiccation or fracturing is not present. Conversely, the SDRI has consistently determined a significantly higher hydraulic conductivity than Shelby tube samples in barrier soil layers where large-scale desiccation has occurred[1,2].

5. Freeze-thaw cycles do not appear to play a significant role in causing hydraulic degradation in barrier soil layers constructed of cohesive silty clay material.

   Freeze-thaw cycles have long been suspected of being a major contributor to degradation of silty clay barrier soil layers and protective measures to prevent frost penetration have frequently been implemented. The twelve inch thick marine silty clay barrier soil layer at WMDSM was located under only two feet of overburden in an area of Maine where the average frost depth exceeds five feet. It thus would have been exposed to numerous cycles of freeze-thaw without any observable or measurable detrimental impact to its hydraulic properties.

9.2 Recommendations

1. A barrier soil layer alone should not be used within a landfill final cover system where site-specific public health and/ or environmental risk factors, or landfill hydraulics, indicate the need for a barrier layer with a hydraulic performance equal to or better than 1×10^{-6} cm/sec, and likely 1×10^{-5} cm/sec. In these circumstances, if a low hydraulic conductivity soil is used, it should be part of a composite system with a geomembrane, or possibly a geosynthetic clay liner (GCL).

2. Public and private concerns alike should continue and intensify efforts to develop and utilize alternatives to soil, used as the sole barrier, within landfill final cover systems.

3. Comprehensive test pad programs should be considered an acceptable practice for barrier soil layer installations and used to verify that the material, equipment, and methods of placement and compaction are able to remold the soil, bond all lift interfaces, and achieve hydraulic performance requirements. Comprehensive CQC and CQA procedures must be developed and implemented to assure the success of any test pad program.

4. The relative importance and benefits of the practice of placing insulation layers above composite landfill liner systems, for the purpose of barrier soil layer frost protection, should be further explored through further testing. We caution, however, that frost protection may still be necessary for leachate collection systems or for other geotechnical reasons.

5. Another composite cover system, consisting of a geomembrane overlying a silty clay barrier soil layer that has been in place for a number of years, should be located and tested in a manner similar to what was done at WMDSM to further confirm the findings of this investigation. Further, the Cumberland Landfill should be re-tested to confirm our expectation that its barrier soil layer will eventually undergo hydraulic degradation similar to what was documented at the Waldoboro and Yarmouth Landfills. Finally, it would be valuable to test a silty clay barrier soil layer that underlies a GCL in a cover system to evaluate whether the GCL provides the same moisture retention benefits as a geomembrane.

9.3 Acknowledgements

The Solid Waste Engineering Unit of the Division of Technical Services wishes to thank the following for their assistance and participation in the 2003 SDRI testing program:

Waste Management Disposal Services of Maine, Inc.
H.E. Sargent, Inc.
The Division of Solid Waste Management

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